Development of a Powder Metallurgical Technique for the Mass Production of Carat Gold Wedding Rings

Peter M Raw

Consultant to Engelhard-CLAL UK Ltd, Chessington, Surrey, UK

Received: 26 August 2000

The development is traced of a press and sinter, powder metallurgical process for the production of carat gold wedding rings. The paper includes experimental data on powder production, powder pressing and sintering as well as details of the production process now fully adopted for the mass production of rings. Properties of the new rings compare favourably with those produced by traditional methods as well as offering significant cost savings.

The techniques in widespread use for the production of carat gold items of jewellery almost all involve melting and casting as an initial step (electroforming is the obvious exception but this has very limited application, being largely used to produce intricate, hollow jewellery).

Investment casting of jewellery involves a number of process steps which can be difficult to control and can lead to technical problems with resultant reject products (1, 2). Static casting of ingots and continuous casting of sheet ingot, rod and tube are the initial steps in the production of semi-finished carat golds, (sheet and strip, wire and tube), which are then used for the manufacture of rings, chains, stampings, bracelets, bangles, necklaces, coins and medallions and a variety of items in which solder joining of individual components is a key element.

One common thread running through all these processes is the relatively low yield of finished product compared with the make-up weight of the original melt charges. Typically the yield is less than 50% and, in some cases like coins, medallions, stampings and rings, it can be very much less than this. Frequently the time taken to produce items can be lengthy because of the need both for regular heat treatment or annealing of items at various stages of manufacture and for periodic surface treatments (milling, pickling, scratch brushing, finishing, polishing and burnishing) which are applied to develop and maintain a highly reflective and blemish-free finish to the jewellery.

These factors have a direct impact on the manufacturing costs of the jewellery. Low yields increase the quantity of gold needed to service the business : they may also lead to increased recycling with the attendant dangers of impacting adversely on the alloy purity and, hence, product quality. On the other hand, if the scrap is refined, this adds further to the costs. Lengthy production times also contribute significantly to the gold financing costs of manufacture and to labour costs.

Some of these issues can be addressed by the use of powder metallurgy which, in its basic form, involves producing alloy powder, mechanically compacting the powder into a handleable form and then heating the pressed compact (sintering) at a temperature below the melting point of the alloy to develop the desired properties. The attractions of this approach lie in the potential for producing net shape or near net shape products utilizing a very few process steps. In this way product yields are maximized and manufacturing times are minimized, both leading to reduced costs.

The development of powder metallurgy as a recognised industrial technology can be said to go back as far as the end of the 18th Century when it was used in the production of platinum and then, more recently, when it was used to consolidate tungsten for electric light bulb filaments about 100 years later. Both were examples of products which could not be made by any other means at the time. Refractory metals and then some alloys of copper, nickel and iron also were made using powder metallurgy but it is in recent years that the technology has really advanced, largely as a result of the automobile industry recognizing the cost benefits of large scale production of iron-based components which require little or no finishing. In North America alone the automobile industry utilizes powder-metallurgically produced parts worth well over $1 billion.

The use of powder metallurgy for finished part production usually involves the need for dies in which the powder can be compacted. This means that, to some extent, mass production of components is needed to justify die costs, a situation which goes without saying in the automobile industry, but is far less common in jewellery manufacturing. Nevertheless, there are areas of jewellery production which can be regarded as potential candidates for a powder metallurgical approach.

Investment casting is, perhaps, the predominant mass production technique in gold jewellery manufacture and metal powder injection moulding (MIM) is currently being seriously considered as an alternative. Fine alloy powder is mixed with a polymer binder and injected using heat and pressure into a permanent die cavity, which can be complex in shape. After solidification, the component is removed, thermally treated to remove the binder and then sintered to achieve densification and metallurgical bonding of the powder. A review of this technology and of the potential technical and economic attractions of the process as an alternative to investment casting of carat gold products has been published (3), but the jewellery industry awaits commercialization on a significant scale.

On the other hand, press and sinter processing of powders is a somewhat simpler approach but is most suited to products which possess a degree of symmetry, such as wedding bands or rings, coins, medallions and watchcases. This paper describes the development of the technique at Engelhard-CLAL UK Ltd (4, 5) as a means of mass producing carat gold wedding rings in what is believed to be the first significant application of powder metallurgy to the fabrication of precious metal jewellery.

BACKGROUND

The impetus for the development work at Engelhard-CLAL came from identifying those manufacturing processes which gave a low yield of carat gold jewellery products, and wedding ring production fell into this category. The ring-making process at that time involved melting and continuously casting carat gold alloy and rolling it to strip, ensuring a high quality surface finish. Washers were then blanked out of the strip and converted into finished rings by a series of cone pressing and ring rolling operations (6). Numerous annealing steps were necessary during the processing. Due particularly to the attention paid to strip quality, the yield of strip compared with the melt weight of alloy was about 65%. The yield of blanked washers and, hence, rings compared with the weight of strip was about 45%. Thus the overall yield of rings from the original melt was only 30%, leaving 70% of the melted weight of alloy to be recycled or refined.

In engineering terms the symmetrical nature of the rings made them ideal candidates for powder metallurgical production by a press and sinter route. In economic terms a powder manufacturing route offered the prospect of significantly fewer process steps and yields of, perhaps, as much as 90%: a significant improvement compared with the traditional route (7). These were the factors which led Engelhard-CLAL to initiate an investigative project.

INITIAL PROPOSALS

The approach adopted was to investigate the following aspects:

- Powder production
- Pressing into hollow cylinders
- Sintering
- Re-pressing or squashing the sintered compacts
- Re-sintering
- Ring-rolling to finished rings

The material selected for the trials was a standard 9 ct yellow gold alloy that was already used extensively for wedding ring production and which contained silver, copper and zinc. The sizes of cylindrical compact chosen were 13 mm OD by 9 mm ID and weighing 3.3 g, and 12 mm OD by 9 mm ID and weighing 1.8 g: *ie* those which were suitable for producing the most common sizes of ring.

Powder

The requirements for the powder were that it should be of a size and shape that would ensure the production of pressed compacts with sufficient mechanical strength (green strength) to allow ejection without cracking from the die used for pressing, and handling and transfer to the sintering furnace without breakage or crumbling.

Green strength is believed to be partly a result of cold welding between individual compacted powder particles but mainly due to mechanical interlocking of particles. Thus finer particles give more contact points and so are more desirable than coarser powders, while irregular-shaped powders give more interlocking and are consequently preferable to spherical particles.

Because of existing expertise and equipment at Engelhard-CLAL, atomization was chosen as the powder

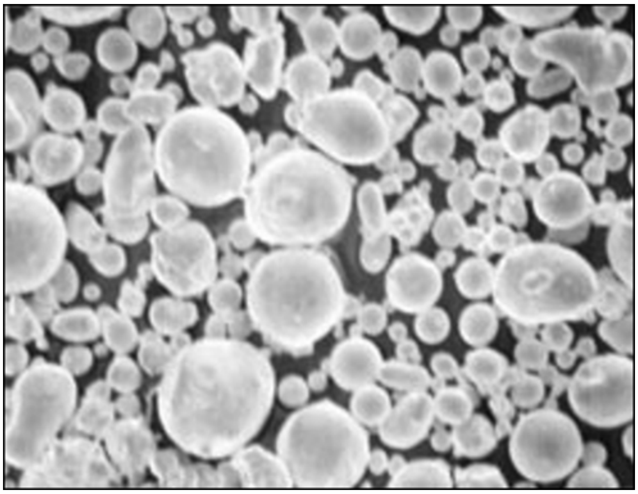

Figure 1 *Scanning electron micrograph of gas-atomized 9 ct yellow gold powder (x 500)*

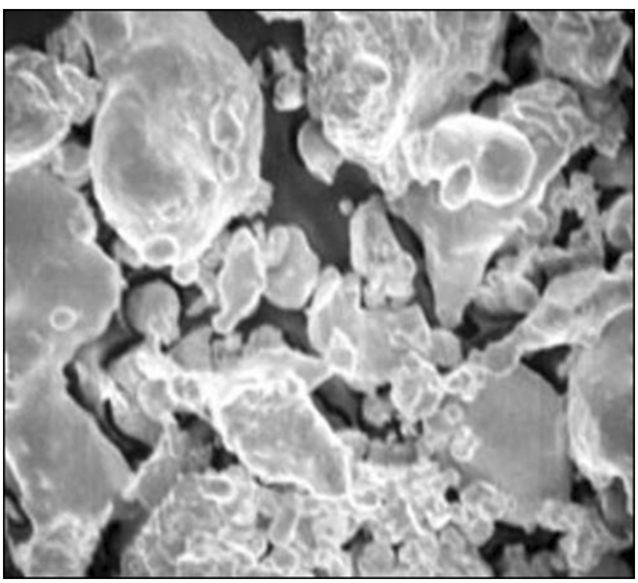

Figure 2 *Scanning electron micrograph of water-atomised 9 ct yellow gold powder (x 500)*

manufacturing technique. Atomization involves breaking up a thin stream of molten metal or alloy into very fine droplets using high pressure gas or water jets, the droplets solidifying in the atomizing chamber into solid particles (8). Gas atomization, with a relatively-slow solidification rate, tends to produce spherical powders as surface tension forces act on the liquid droplets. Water atomization, with a much faster solidification rate, produces irregular particles as there is much less time for surface tension to come into play. Scanning electron micrographs of the two types of 9 ct gold powder are shown in Figures 1 and 2 where the differences in shape can be clearly seen.

Atomization is especially suited to producing alloy powders, a prerequisite in the present work which was ultimately intended to produce rings in a variety of carat gold alloys.

Pressing

Die compaction using double-action tooling was proposed for the pressing stage. In this way a more uniformly dense compact would be produced than with single-action tooling which, in turn, would lead to more uniform shrinkage during sintering.

Some powders are mixed with suitable organic compounds before pressing and these can act both as a lubricant, reducing die wall friction during pressing, and as a binder to give added green strength. The organic material is then burned off before sintering. However, it was hoped that this procedure would be unnecessary with carat gold powders especially as it was decided to limit the aspect ratio of the compacts (height of pressed compact to wall thickness ratio) during pressing to 3, down from a more-frequently recommended limit of 5.

Dies were proposed to be manufactured out of tool steel.

Sintering

Sintering is a high-temperature heat treatment which results in powder particle bonding and densification of the compact (9). It is a result of solid state diffusion and not melting. The energy for diffusion is provided by the applied heat and so higher sintering temperatures result in greater and more rapid bonding and densification. Because the carat gold alloys almost invariably contain copper and zinc, both of which oxidize readily, sintering has to be carried out in a controlled atmosphere and 95% nitrogen-5% hydrogen was proposed for the trials.

Re-Pressing and Re-Sintering

It was anticipated that the sintered compacts might have densities which would be significantly less than 100% of the theoretical density and that some further operations might therefore be necessary to increase the density of the rings closer to the maximum.

In the traditional ring-making technique the hollow cylinders were squashed to the finished ring width (height) and annealed before ring rolling to finished rings (6). The squashing operation tended to give a convex shape to the inner and outer ring faces which subsequently aided ring rolling. By adopting these procedures for the sintered rings it was felt that, in combination with the subsequent ring rolling, further densification (and, therefore, enhanced mechanical properties and hardness) would result and so these extra stages were proposed to the manufacturing route.

Ring Rolling

The final production stage was identical to that used in the traditional route, namely ring rolling on a Karl Klink machine, as shown in Figure 3.

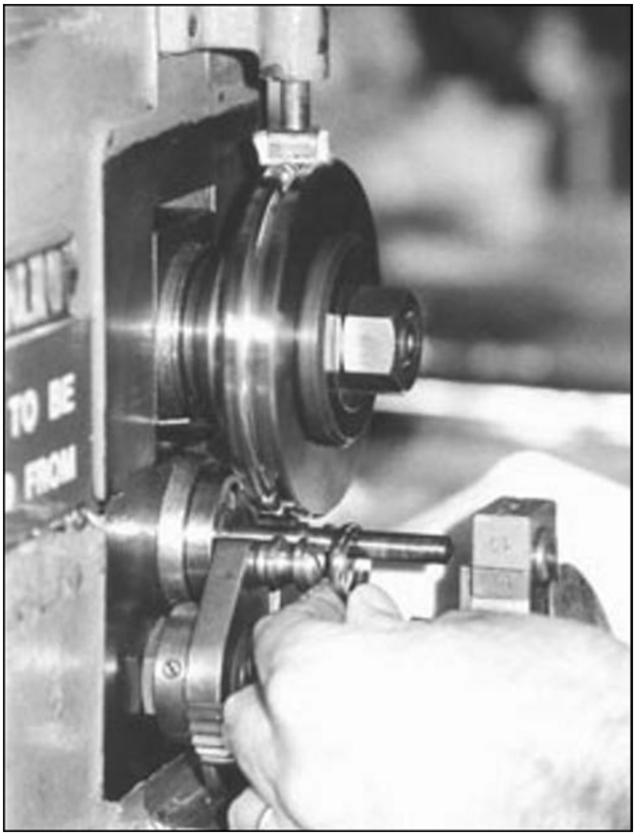

Figure 3 *Production of carat gold rings on a Karl Klink ring rolling machine*

EXPERIMENTAL WORK

There already existed a gas atomization facility at Engelhard-CLAL suitable for preparing carat gold powders when the experimental work was initiated but, recognizing the likely limitations of gas-atomized powder, water-atomized powder was obtained from an external supplier.

A few trials were carried out with gas-atomized powder but all compacts pressed over a wide range of pressing pressures exhibited poor green strength, even when the powder was sieved to <125 μm to eliminate coarse particles, many compacts cracking on ejection from the die. A typical crack in such a compact is shown in Figure 4, probably caused by release of elastic stresses.

All subsequent work took place with water-atomized powders. Two batches of powder were obtained, produced under the conditions shown in Table 1. Each batch was about 5 kg in weight.

Figure 5 shows cumulative size distribution plots for each batch of powder. The mean particle size (50% by weight of powder was below this size, read off from Figure 5) was 75 μm for Batch 1 and 45 μm for Batch 2, the higher melt temperature and atomizing water pressure producing the finer powder. The trials therefore focused on powder from Batch 2.

In order to remove large particles and therefore assist in developing better green strength on pressing, samples of powder were sieved and those which had been sieved to <250, <125 and <106 μm were pressed into 1.8 and 3.3 g compacts in punch and die sets on a laboratory hydraulic press. Various pressures up to 100 tsi were used. Those compacts which were produced from <250 μm powder tended to crack on ejection from the die after pressing and so no further work was conducted on these powder fractions. The other samples gave pressed compacts over a range of pressing pressures which could be easily handled without damage and so subsequent

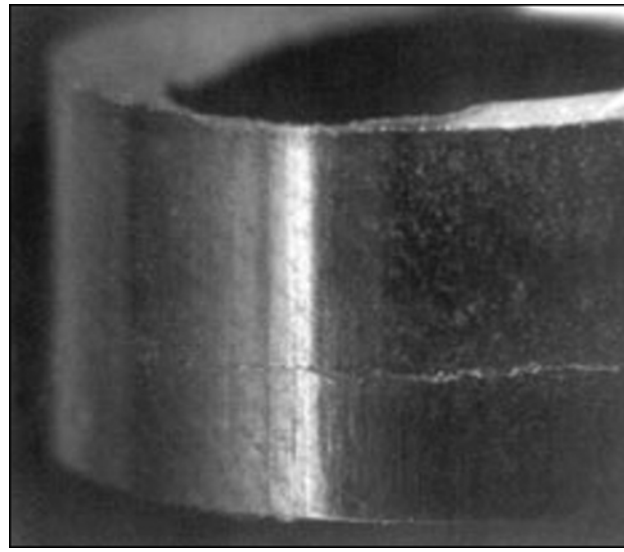

Figure 4 *Cracking in gas-atomized powder compact on ejection from die (x 8)*

Table 1 *Conditions Used to Produce Water-Atomized 9ct Gold Powder*

Parameter	Batch 1	Batch 2
Melt temperature,°C	1025	1068
Tundish temperature,°C	950	1000
Water pressure, psi	2000	4000
Water flow rate, litre/min	41	40
Tundish hole diameter, mm	4	4
Atmosphere	Nitrogen	Nitrogen

work concentrated on <125 μm powder, the size giving the greater yield of usable powder.

Figure 6 shows how green density (pressed density) increased with increase in pressing pressure for 3.3 g compacts, while Figure 7 shows the increase in sintered density with time of sintering at 780°C for 1.8 g compacts pressed at five different pressures. Most densification occurred in the first half-hour of sintering, with little further change after 1.5 hours. The sintering temperature of 780°C was chosen as being the highest practical temperature which could be achieved while still remaining below the solidus temperature of the alloy (800°C). The effect of sintering temperature on sintered density is shown in Figure 8 where it can be seen that the highest practical temperature is needed to achieve the highest density value.

At this stage ring samples produced under various conditions were re-pressed (squashed) and ring rolled but, without exception, all developed transverse cracks, a

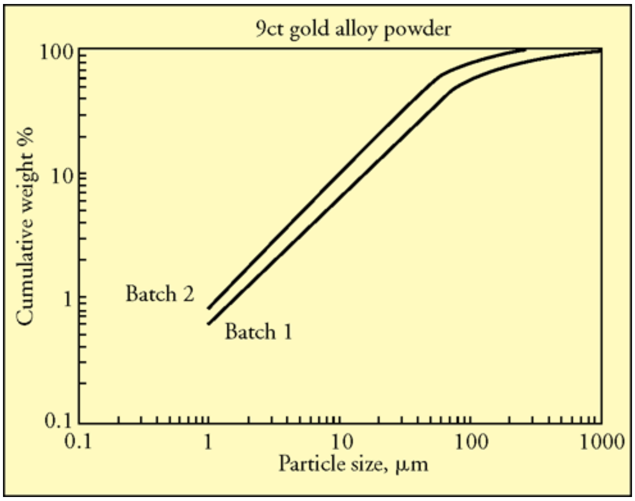

Figure 5 *Log-log cumulative size distribution for water-atomized 9 ct gold alloy powder*

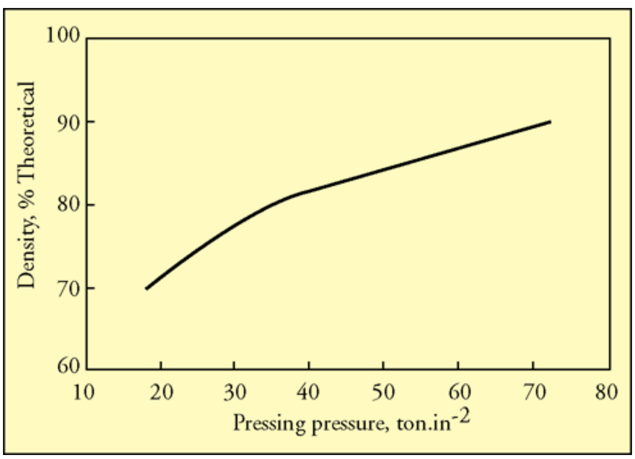

Figure 6 *Variation between pressed density and pressing pressure for 3.3 g compacts in water-atomized 9 ct yellow gold powder*

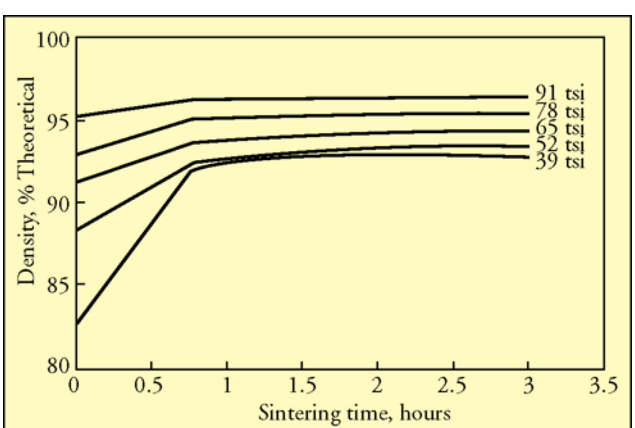

Figure 7 *Relationship between density and sintering time at 780°C for 1.8 g 9 ct gold compacts pressed at different pressures*

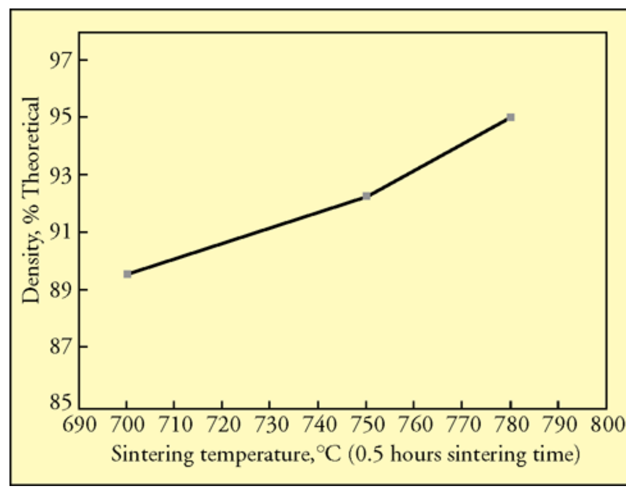

Figure 8 *Effect of sintering temperature on density of 1.8 g compacts in water-atomized 9 ct yellow gold powder*

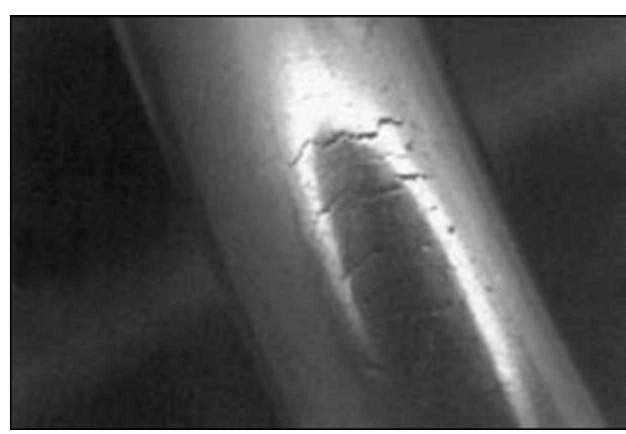

Figure 9 *Surface cracks developed in sintered 9 ct gold powder compacts after re-pressing and ring rolling (x 10)*

typical example of which is shown in Figure 9. An annealing, or re-sintering, operation was then introduced after re-pressing with some improvement but it was not until a 24-hour re-sintering treatment was tried that some crack-free rings were produced.

Fine powders can be expected to adsorb moisture or gas over a period of time if exposed to atmosphere (10) and it was speculated that such adsorption on 9 ct gold powder might be a factor in ring cracking during rolling. A powder vacuum heat treatment was then proposed, initially treating powder at 180°C and 1 millibar pressure. Tests in which samples of the 9 ct gold powder were weighed after exposure to air for various times and again after the vacuum heat-treatment supported this view. The weight loss recorded after the vacuum treatment increased from 0.005% after 2 days exposure to 0.017% after 20 days, 0.045% after 42 days and 0.06% after 55 days. Introducing the vacuum treatment while retaining a long re-sintering time eliminated the cracking on ring-rolling.

At this stage it was possible to define a route by which 9 ct gold rings could be produced on a trial basis in 1.8 and 3.3 g sizes:

- Water atomize 9 ct gold alloy
- Sieve to <125μm
- Vacuum degas at 180°C
- Press at pressures from 65 to 100 tsi
- Sinter for 1.5 h at 780°C in a reducing atmosphere
- Re-press
- Re-sinter for 24 h at 780°C in a reducing atmosphere
- Ring roll to finished size

The quality of the finished rings seemed excellent, an example being shown in Figure 10. The pressed density of typical rings was 85-90% of theoretical and this increased to about 95% after sintering and to 98-99% after re-pressing, re-sintering and ring rolling.

The stages from powder to finished rings are illustrated in Figure 11.

Figure 10 *Finished ring produced from water-atomized 9 ct yellow gold powder (x 3.3)*

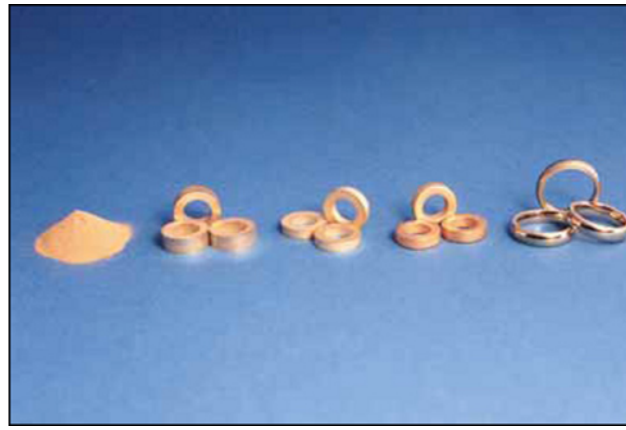

Figure 11 *Stages in the production of 9 ct yellow gold rings from powder*

RING CHARACTERISTICS

Having established an optimized route for ring manufacture from powder, test rings were examined in detail and batches were sent to ring finishers for assessment. The ring finishers are concerned with engraving, diamond cutting, polishing and sizing.

Metallographical examination of rings confirmed there was minimal porosity and that the small amount present was concentrated towards the centre of the rings where it would have no effect on properties or ring quality. Figure 12 shows a metallographic section through a ring in the unetched condition with little apparent porosity. In the etched condition the grain size can be seen (Figure 13) and, by comparison with a section through a conventional ring (Figure 14), a finer size is very apparent. A fine grain size is a characteristic of powder metallurgically-produced materials and may be associated with the presence of very fine, sub-microscopic porosity which can stabilize grain boundaries and make them more difficult to move during recrystallization.

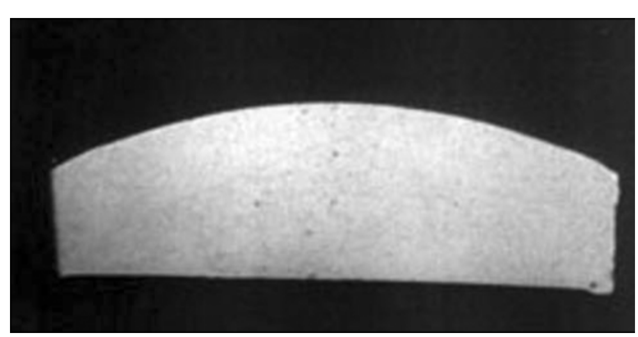

Figure 12 *Metallographic section through finished 9 ct yellow gold ring showing minimal porosity (x 28)*

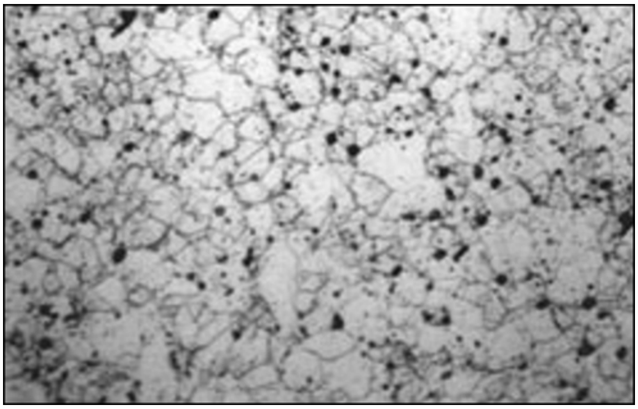

Figure 13 *Metallographic section (etched) through 9ct gold ring produced from water-atomized powder (x 180)*

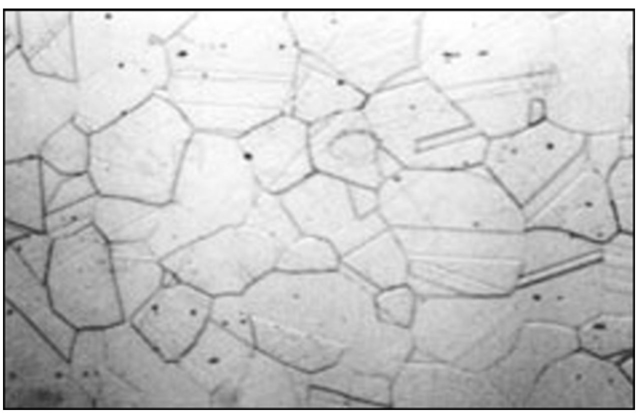

Figure 14 *Metallographic section (etched) through 9 ct gold ring produced by traditional casting and fabrication route (x 180)*

Hardness measurements gave values of 120 Hv for annealed rings made from powder compared with 110 Hv for conventional rings, a difference which would be expected from the grain size differences as long as the density levels approach 100% of the theoretical.

Findings of ring finishers included the remarkable discovery that annealed rings could be sized up from ring size M to Z (11) without the need for any intermediate annealing, equivalent to increasing the internal ring circumference from 52.19 to 68.47 mm. This compares with a capability of sizing from about M to O (52.19 to 54.74 mm circumference) for conventional rings and illustrates a considerable enhancement of ductility although, in practice, sizing more than three ring sizes would be unlikely.

Engraving of the new rings proved somewhat harder to carry out than usual but this was taken as a good sign, indicative of a harder, more wear-resistant material. Furthermore, the engraved patterns were sharper and there were no 'soft spots' which are, apparently, occasionally found in conventional rings and which make engraving more difficult.

The edges of the new rings were found to be more uniform which meant that less finishing (turning or polishing) was needed; in fact most basic rings simply needed a final polish.

FULL-SCALE RING PRODUCTION

Having proved the feasibility of a powder metallurgical route for ring making and established that such rings fully met the requirements of the customers, the process had to be scaled-up in such a way that the proposed new equipment had to be financially justified and it had to meet the foreseen capacity demands of the business. In terms of capital items the needs were for a water atomizer to produce the powder, an automatic press to make the pressed compacts and a sintering furnace.

Powder Production

From the earlier work the requirements for powder were that it should be <125 μm sieve size while, economically, a high yield of this powder size was necessary, ideally in excess of 90%. Although there was no water atomizer suitable for gold powder manufacture at Engelhard-CLAL, a gas atomizer was available and this was converted into a water atomizer. After several trials, conditions were established for producing 9 ct gold powder with a 90% yield <125 μm and these are shown below:

- Melt temperature 1070°C
- Tundish temperature 1100°C
- Water pressure 2500 psi
- Tundish hole diameter 4.7 mm

A nitrogen atmosphere was used inside the atomization chamber.

Powder Pressing

The major requirement for a press was to allow automatic die filling, pressing and ejection of the compacts while achieving a constant compact weight. The operating requirements are shown schematically in Figure 15. A suitable hydraulic press was identified and purchased. Powder from a hopper is fed through a hose into a shaker from where it is transferred into the die cavity. The amount of powder dispensed is determined by the volume of the die cavity. The tooling used in the press is a double-action floating die system where the die is mounted on a hydraulic cylinder. As the top punch enters the die and starts to compact the powder, friction between the powder and the die wall causes the die to move down,

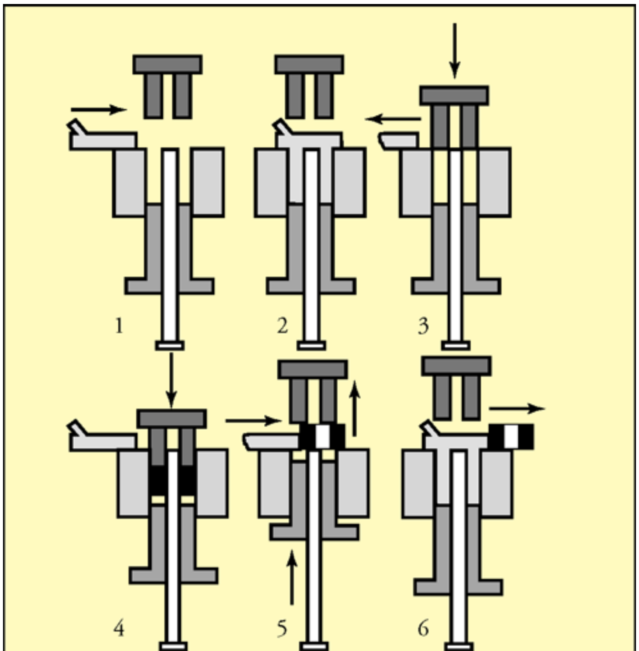

Figure 15 *Schematic outline of powder compaction sequence*

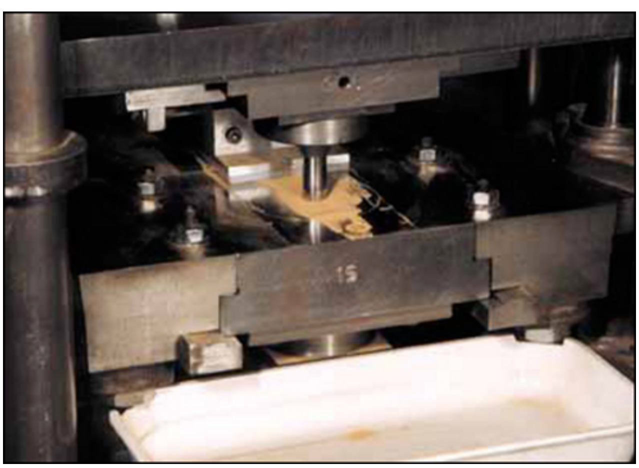

Figure 16 *View of powder press during compaction*

which has the same effect as the bottom punch moving up. After pressing, the compact is ejected from the die and pushed into a collection tray by the shaker which then refills the die cavity. A complete cycle takes between 6 and 10 seconds and so compacts can be produced at rates of up to 10 parts per minute, or 600 per hour. The operation of the press is shown in Figures 16 and 17.

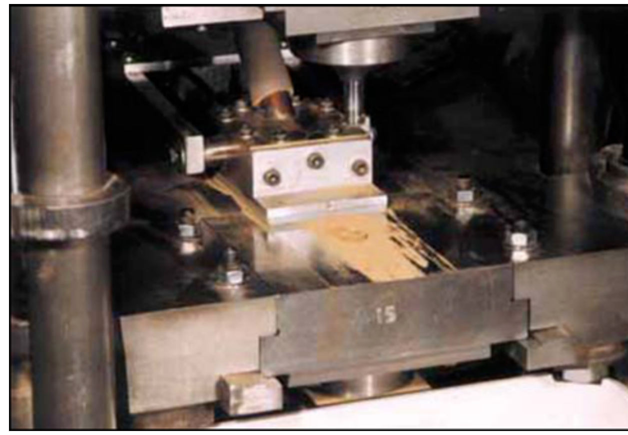

Figure 17 *View of powder press after ejection of pressed compact from die*

During some of the high pressure pressing operations (pressures approaching 100 tsi) evidence of 'mushrooming' of the tool steel punch was found and so for subsequent tooling high speed steel was used with a surface hardening treatment being applied. Pressing pressures have also been restricted to 60 tsi.

Sintering

The furnace required for sintering had to be flexible enough to cope with high throughputs, different sintering times up to 24 hours, temperatures at least up to 1000°C, allow the use of a reducing atmosphere and possess a facility to enable quenching of the sintered rings. A rotary hearth furnace was specially designed by Carbolite to meet this specification. Inconel trays capable of holding several hundred rings are loaded into the furnace, as shown in Figure 18, and the furnace rotates in 10° intervals, allowing periodic addition of other trays. The

Figure 18 *Furnace used for sintering carat gold powder compacts*

speed of rotation is adjusted to give the required sintering time. After sintering is complete, the trays of rings are pushed out of the furnace chamber into a water quench tank. The furnace operates under an atmosphere of 95% nitrogen-5% hydrogen.

PROCESS DEVELOPMENTS

Full-scale production of rings using powder metallurgy began at Engelhard-CLAL at the end of 1997 and, since that time, it has grown to take over completely from the traditional ring-making route, to produce rings in a range of sizes and to extend to a complete range of carat gold alloys. The process itself has also evolved during that time.

Carat Gold Alloys

Once the technique had been proven for 9ct yellow gold, attempts were made to extend it to a range of different alloys. It quickly became apparent that adjusting the alloy melt atomization temperature and pressed compact sintering temperature in relation to alloy melting range was sufficient to allow new procedures to be defined for ring manufacture in these alloys. The parameters established are shown in Table 2.

In all cases the yield of powder <125 µm in size was about 90%. Pressing pressures for the powder compacts were in the range 30-35 tsi.

Different sizes of ring were also readily manufactured and the technique is now used to make rings varying in weight from 1.5 up to 20 g.

Powder Production

On occasion it was found that the fine powder did not flow as readily as required for easy die cavity filling. This problem was resolved by adding a small quantity of a surfactant to the water used to atomize the carat gold alloys.

Powder is currently atomized in 8-10 kg batches, one batch being sufficient for about 2000-2500 rings. After vacuum treatment the powder is tumbled to ensure each batch is homogeneous, assayed to ensure conformance to caratage and stored in sealed plastic containers.

Powder Pressing

For each new batch of powder a few rings are pressed according to the operating procedure for the particular alloy and size of ring and the weight and height of the pressed compacts are determined. If necessary, minor adjustments are then made to the size of the die cavity (by re-positioning the lower punch) to achieve the desired weight of ring, and to the pressing pressure to achieve the correct ring height and, therefore, pressed density. The press is then set to operate automatically to produce up to 600 compacts per hour until the batch of powder is used up.

Determination of the weight of pressed compacts selected at random shows very good consistency. For example, for nominally 4 g compacts in 9 ct white gold, the average weight of 20 rings was 4.006 g with a minimum weight of 3.938 g and a maximum weight of 4.040 g being recorded. The equivalent figures for twenty 18 ct yellow gold compacts of nominally 6.4 g weight were an average of 6.401 g, a minimum of 6.369 g and a maximum of 6.435 g. Normally there is an allowable tolerance of at least 0.1 g either side of the nominal weight.

Sintering

Investigating the need for both a sintering operation after pressing and a re-sintering operation after re-pressing led to the finding that increasing the time of the first sintering operation to 24 hours allowed the elimination of re-sintering. The sequence of operations for converting powder to rings is now:

- Press compacts at 30-35 tsi
- Sinter for 24 hours
- Re-press rings
- Ring roll to finished size
- Anneal

Table 2 *Processing Parameters for Carat Gold Alloy Rings Made from Powder*

Gold Alloy	Melting Range,°C	Atomization Temperature,°C	Sintering Temperature,°C
9ct Yellow	800-895	1070	780
9ct Red	970-990	1180	860
9ct White	875-940	1100	840
14ct Yellow	845-895	1070	820
18ct Yellow	875-920	1080	825
18ct White	1235-1300	1490	1000

The final annealing operation is to allow any subsequent sizing operations and, in the case of 9 and 14 ct gold alloys, remove the risk of stress corrosion.

A modification has been made to the containers in which the compacts are sintered. The long sintering times resulted in some loss of zinc from the zinc-containing carat gold alloys which, in turn, led to slight over-caratage of the rings. By putting a loose-fitting lid onto the containers the problem was effectively eliminated. The containers themselves have a few holes drilled in the sides to allow water to enter during the quenching operation after sintering.

CONCLUDING REMARKS

The press and sinter technique has now enjoyed nearly three full years of use at Engelhard-CLAL and, in the period up to August 2000, over 500,000 carat gold rings had been produced.

While the technique is a very simple and straightforward example of the use of powder metallurgy in producing net-shape products, it is believed to be the first time that it has been used in the mass production of gold jewellery. The technique is widely applicable to carat gold alloys while the rings themselves have significant hardness and ductility benefits compared with conventionally-produced rings, largely due to the fine grain size.

The overall process yields of greater than 85% compare extremely favourably with yields of about 30% for conventional rings and bring a range of economic benefits by reducing metal financing, recycling, refining and labour costs.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contribution to this development made by a number of staff at Engelhard-CLAL, particularly Terry Taylor, and to thank Mr Akin Akintola, Business Support Director at Engelhard-CLAL UK Ltd, for his permission to write this paper.

Figure 15 is reprinted with permission from Metal Powder Industries Federation, 105 College Road East, Princeton, New Jersey, USA.

ABOUT THE AUTHOR

Peter Raw is a graduate of Cambridge University in Natural Sciences (Metallurgy). He was successively Production Director and Development Director at Engelhard-CLAL UK Ltd between 1984 and 1996 when he became a precious metals consultant. In this latter role he has often worked for the World Gold Council and has published several papers in *Gold Technology*.

REFERENCES

1 'Investment Casting', Technical Advisory Manual for Goldsmiths, World Gold Council, 1995

2 Handbook on Casting and Other Defects in Gold Jewellery Manufacture, World Gold Council, 1997

3 J.T. Strauss, *Gold Technology*, No 20, November 1996, 17-29

4 Engelhard-CLAL Ltd, International Patent Application No PCT/GB98/02733, 1998

5 Engelhard-CLAL Ltd, South African Patent No 98/8340, 2000

6 P.M. Raw, *Gold Technology*, No 27, November 1999, 2-8

7 J.T. Strauss, *Proc of the Twelfth Santa Fe Symposium on Jewelry Manufacturing Technology*, Met-Chem Research Inc, 1998, 425

8 J.J. Dunkley, in 'Powder Metallurgy – An Overview', The Institute of Metals, 1991, pp. 2-21

9 W.A. Kaysser, in 'Powder Metallurgy – An Overview', The Institute of Metals, 1991, pp. 168-182

10 C.G. Goetzel, 'Treatise on Powder Metallurgy – Volume 1', Interscience Publishers Inc, 1949, pp. 123-125

11 British 'Wheatsheaf' system of ring sizing now largely superseded by International Standard ISO 8653